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(71) Applicant: FUSION SYSTEMS CORPORATION [US/US]; 7600 Standish Place, Rockville, MD 20855 (US).

(74) Agents: ABRAMSON, Martin et al.; Pollock, Vande Sande & Priddy, Suite 800, 1990 M Street, N.W., Washington, DC 20036 (US).

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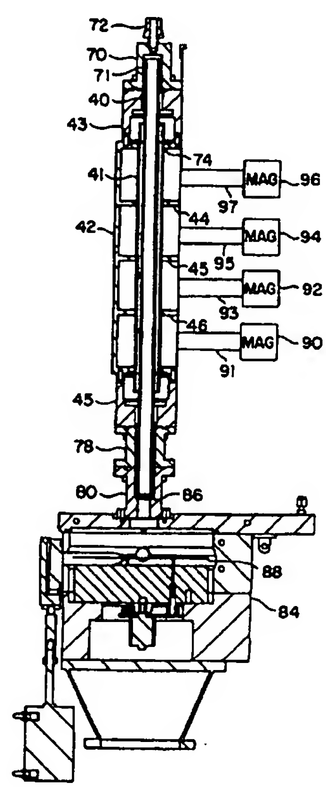
(57) Abstract

A method of removing material from a substrate (88), and a plasma discharge device wherein a plasma is excited by microwave energy (91, 93, 95, 97) having an electric field which is azimuthally and axially uniform in relation to the plasma tube (40). The microwave cavity is divided longitudinally into sections by conducting partitions (44, 45, 46), each of which is separately fed with microwave energy (91, 93, 95, 97), and the plasma tube (40) extends through openings in the partitions (44, 45, 46).



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PLASMA DEVICE AND METHOD UTILIZING AZIMUTHALLY AND AXIALLY UNIFORM ELECTRIC FIELD

The present invention is directed to an improved method for removing material from a substrate, and to an improved plasma discharge device.

In the manufacture of semiconductor devices, it is frequently necessary to remove a substance from a substrate. One example of this is the residue which may remain on a silicon wafer after an etching step is completed. Such residue is frequently composed of a polymeric material which may be present in the form of "veils", and is caused by overetching during etch processes. Another example is the controlled removal of thin film materials such as silicon dioxide or polysilicon from a silicon wafer. The present invention is broadly applicable to processes for removing a substance from a substrate, and for example, would include residue removal, chemical downstream etching (CDE), and etching processes.

It is known to use plasma discharge devices to remove a substance from a substrate, and these may be of the "afterglow" type, wherein it is the afterglow of the plasma rather than the plasma itself which accomplishes removal. While the gas used in the plasma discharge is frequently oxygen, as for ashing applications, it is known to use fluorine containing gases for other applications, for example, where materials such as heavily metallized polymeric residues are to be removed.

In a plasma discharge device, a gas is flowed through a plasma tube which is located in a microwave cavity, and a plasma is excited in the gas by the microwave energy. While the tube is typically made of quartz, when fluorine containing gases are used, it is necessary to make the tube of a fluorine resistant material such as Al_2O_3, (alumina), single crystal Al_2O_3 (sapphire), Al_2N_3, Z_nO, CaF_2 or M_gF_2.

It was found that when a sapphire tube was excited in a system designed for a quartz tube, cracking of the tube occurred. It was discovered that the problem was caused by unequal heating of the sapphire tube due to a non-uniform electric excitation field. Unlike quartz, sapphire is a material which is inclined to crack when heated unequally.

In accordance with the present invention, the problem is solved by providing a resultant microwave excitation electric field which is substantially uniform in the azimuthal and axial directions of the tube. Such a field will cause substantially equal heating of the tube in the azimuthal and longitudinal directions, thus obviating cracking.

The resultant azimuthal and longitudinal uniformity may be provided by modes including the rectangular TM_{110} mode or the cylindrical TM_{010} mode, or possibly by a combination of other modes, the resultant of which is the desired uniformity.

In order to create the conditions necessary to excite and support the rectangular TM_{110} or cylindrical TM_{010} modes, such that it is the dominant driven mode, it is necessary to use a relatively short microwave cavity. This would ordinarily dictate using a correspondingly short plasma tube. However, a problem caused by using a short plasma tube may be that the longitudinal temperature gradient is too great at the ends of the tube where there is a transition from inside the cavity, where there is a field, to outside the cavity where there is no field, thus causing cracking.

To solve this problem, a relatively long microwave structure is provided, which is divided into lengthwise sections by partitions. The plasma tube is fed through a hole in each partition, and thus runs the length of the microwave structure, while each of the lengthwise sections is separately fed with microwave energy. Each section thus appears to the incoming microwave energy to be a separate cavity of relatively short length, thus promoting the formation of the correct mode, while the plasma tube is relatively long, thus obviating any problems with cracking.

The invention will be better understood by referring to the accompanying drawings, wherein:

Figure 1 shows a prior art plasma processing device.

Figure 2 shows electric field intensity distribution in the rectangular TM_{110} mode, which provides azimuthal and axial uniformity.

Figure 3 shows a microwave structure employing the invention

Figures 4 and 5 shows a more complete device.

Figure 6 shows an embodiment which utilizes multiple magnetrons.

Figure 7 shows an embodiment which utilizes microwave chokes at the partitions.

Referring to Figure 1, a known plasma processing device 1 which uses a quartz plasma tube 6 is depicted. The tube runs through microwave cavity 4, and exits the cavity through microwave seal 7.

When microwave power is provided to the cavity by magnetron 12, a plasma is excited in tube 6. The plasma does not exist on the other side of seal 7, but rather it is the "afterglow" of the plasma which exits from the end of the tube and is used for the processing of work piece 11.

The quartz tube 6 may carry oxygen in which the plasma is excited. As discussed above, when fluorine is required by the

process, the quartz tube must be replaced by a tube made of a fluorine resistant material, for example, alumina, or sapphire.

However, when a sapphire plasma tube is operated in a device such as is shown in Figure 1, cracking of the tube occurs. It was discovered by the inventors that the cracking is caused by the unequal heating of the tube caused by the non-uniform electric field component of the microwave field, which for example, in the device of Figure 1, is in the TE_{102} mode.

In accordance with the present invention, microwave energy is provided having an electric field which is substantially uniform in the azimuthal and axial directions of the tube. Such an electric field will heat the tube substantially uniformly in the azimuthal and axial directions of the tube, which will prevent or minimize the formation of temperature stresses due to unequal heating. As used herein, the term "azimuthal direction" applies to tubes having both circular and non-circular cross-sections, and means the direction which follows the periphery of the tube in a plane which is perpendicular to the axial direction.

The rectangular TM_{110} and circular TM_{010} modes both provide substantial azimuthal and axial uniformity for a tube of circular cross-section. In Figure 2, the idealized electric field intensity distribution 20 for such modes are depicted (shown in rectangular cavity 22). The intensity distribution may be viewed as concentric cylinders having azimuthal and axial uniformity

with the strength increasing towards the center. There is negligible variation in field strength over the relatively small radial dimension of the tube.

A relatively short cavity favors the formation of modes having azimuthal and axial uniformity, which suggests the use of a correspondingly short plasma tube. In a practical system, process etch rates are related to microwave input power. When an input power that attains an acceptable etch rate is used with a short plasma tube, the power density is such that an unacceptably large thermal gradient exists at the ends of the tube, which may cause cracking.

This problem is solved by using a microwave enclosure which is partitioned into lengthwise sections. Referring to Figure 3, microwave enclosure 42 is a rectangular box which is partitioned into lengthwise sections by partitions 44, 45, and 46 having plasma tube 40 passing therethrough. While four sections are shown in the embodiment which is illustrated, fewer or more sections may be used. Each partition has an opening through which the plasma tube passes. Each section is separately fed with microwave energy. Thus, each section appears to be a relatively short cavity to the incoming microwave energy, promoting the formation of modes having azimuthal and axial uniformity, and preventing the formation of modes such as the TE_{101}, TE_{102}, etc., which do not. However, the total length of the plasma tube is relatively long, thus ensuring that the power

density in the tube is such that the temperature gradient at the tube ends is within acceptable limits.

Outer tube 41 surrounds the plasma tube inside the cavity. The outer tube is slightly separated from the plasma tube, and air under positive pressure is fed between the two tubes to provide effective cooling of the plasma tube. Tube 41 would typically be made of quartz.

The openings in the partitions 44, 45, and 46 through which the concentric tubes are fed are made larger than the exterior dimension of the plasma tube. There is microwave leakage through such openings which causes a plasma to be excited in the part of the tube that is surrounded by the partition. Such leakage helps reduce thermal gradients in the plasma tube between regions surrounded by partitions and regions that are not. If an outer tube is not used (cooling provided in some other manner), the openings in the partitions are sized so that there is a space between the plasma tube and the partition to provide such microwave leakage. In the embodiment shown in Figure 3, there is a space between the outer tube and the partition.

Figure 3 also shows an iris plate 50 which covers the open side of the microwave structure, and is effective to feed microwave energy into the adjacent sections. Plate 50 is a flat metallic plate having irises 52, 54, 56 and 58, through which the microwave energy is fed.

While the invention is applicable to devices where either the plasma or the afterglow from the plasma is used to remove material, the preferred embodiment is an afterglow device. Microwave traps 43 and 45 are provided at the ends to prevent microwave leakage. Such traps may be of the type disclosed in U.S. Patent No. 5,498,308, which is incorporated herein by reference. Air seals/directional feeders 47 and 49 are provided for admitting cooling air and feeding it to the space between the concentric tubes. Air seal/directional feeder 51 is shown at the outlet end, and a fourth such unit is present, but is not seen.

Figure 4 shows a more complete device as assembled. Magnetron 60 provides microwave power, which is fed through coupler 62 to a waveguide supplying a TE_{10} mode, having mutually perpendicular sections 64 and 66. The length of waveguide section 66 is adjustable with moveable plunger 82. The bottom plate of waveguide section 66 in the Figure is iris plate 50, which couples microwave energy into partitioned microwave structure 42, through which the plasma tube extends; thus, a plasma is excited in the gas flowing through the plasma tube.

Referring again to Figure 4, it is seen that end cap 70 abuts microwave trap 43, and fitting 72 having a central orifice for admitting gas to the plasma tube extends into the end cap. The plasma tube is supported at this end by O ring 71 in the end cap. The outer tube 41 is supported at its ends by abuttment against microwave traps 43 and 45. Spacer 78 is present to provide the proper spacing in relation to the process chamber.

The other end of the plasma tube is located in end member 80, and has an orifice 86 for emitting gas into the process chamber.

The process chamber 84 includes retractable wafer support pins 90 and 91, which support wafer 88, to be processed. Chuck 92 is for providing the correct heating to the wafer during processing. One or more baffle plates may be present above the wafer to promote even distribution of the gas.

Referring to Figure 5, an exterior view of the device is shown. The reference numerals in Figure 5 correspond to those which are in the other Figures.

In the preferred embodiment, microwave enclosure 42 is dimensioned to support the rectangular TM_{110} mode and the enclosure 42 may have a square cross section. The dimensions of the cross sections are such that the TM_{110} mode is resonant. The length of each section is less than $\lambda_g/2$ where λ_g is the guide length within the cavity of the TE_{104} mode.

In an actual embodiment which was built, the magnetron frequency was 2443 MHz, the microwave enclosure was 3.475 - 3.5 inches on each side, and the length of each of four sections was 2.875 inches. A sapphire tube having an ID of about .900" and an OD of about 1.000" was used, and a gas of 85% O_2, 5% He, 10% NF_3 was flowed through the tube for removing residue of polymeric materials in the form of veils which are caused by overetching. The power density was about 36 watts/in^3.

Rather than using the iris plate 50 to feed microwave energy into the device, a separate microwave power generating source and waveguide may be used for each section. An embodiment so constructed is shown in Figure 6, which is identical to Figure 4 except for the microwave feed arrangement.

Referring to Figure 6, separate magnetrons 90, 92, 94, and 96 are depicted, which feed into respective waveguides 91, 93, 95, and 97. There is a slot in each section of plate 51, by which microwave energy enters the respective sections. The direction of the slots may be perpendicular to the long direction of the plasma tube. In the alternative, coupling may be by way of respective coupling loops.

The use of separate magnetrons may help in achieving equal power in the respective sections. It affords more control than the prior arrangement and allows the input power to a given cavity section to be varied, e.g., to compensate for leakage.

Figure 7 depicts a microwave choke which may be used around the plasma tube at the partitions to prevent microwave leakage between cavity sections. This is useful when used in connection with the embodiment of Figure 6, since if control is to be afforded to the individual magnetrons, leakage between the sections must be minimized. Of course, if leakage is too great between the sections in the embodiment shown in FIgures 3 and 4, then chokes should be used there also.

In the embodiment shown in Figure 7, the microwave choke is an annular ring 100 made of dielectric material, e.g., teflon, quartz, or alumina. Referring to the figure, cavity partition 102 is cut out at the inside edge with recess 104, into which the annular ring 105 fits. Another annular piece of the partition, 106, overlies piece 102 and the dielectric ring. Pieces 102 and 106 are shown separated for clarity, but abut each other in the assembled device.

As discussed above, the invention finds a particular use with plasma tubes which are made of a material which is inclined to crack when heated unequally. One example of such materials are those having a linear thermal expansion coefficient greater than $7 \times 10^{-7}/K°$ at operating temperature. However, the invention may also be used with other plasma tubes, for example those made of quartz, as the uniform field will tend to keep the plasma off the tube wall and may provide improved lifetime of the quartz.

A quartz tube may be used with a fluorine containing gas by coating the inside of the tube with a fluorine resistant coating such as Al_2O_3, CaF_2, fluorosilicade glasses AlN, or other fluorine resistant coating.

An improved method and device for removing a material for a substrate has been disclosed. It should be appreciated that while the invention has been disclosed in connection with illustrative embodiments, variations will occur to those working

in the art, and the scope of the invention is defined by the claims appended hereto as well as equivalents.

CLAIMS

1) A method of removing material from a substrate comprising,

providing an elongated tube,

flowing gas through said tube,

coupling microwave energy to said gas to excite it to a plasma, which microwave energy has an electric field which is substantially azimuthally and axially uniform in relation to said tube, and

utilizing said plasma or the afterglow therefrom to remove said material from a substrate.

2) The method of claim 1 wherein said microwave energy is in the rectangular TM_{110} or cylindrical TM_{010} mode.

3) The method of claim 1 wherein said tube is made of a material which is inclined to crack when heated unequally.

4) The method of claim 3 wherein said gas comprises fluorine or a compound thereof, and said tube is made of a fluorine resistant material.

5) The method of claim 4 wherein said material has a linear thermal expansion coefficient greater than $7 \times 10^{-7}/K^{\circ}$ at operating temperature.

6) A plasma discharge device for removing material from a substrate, comprising,

a microwave cavity,

a plasma tube passing through said microwave cavity,

means for providing gas to said plasma tube,

said cavity during operation having inside it an electric field for exciting said gas to a plasma, which is substantially azimuthally and axially uniform in relation to said tube, and

means for utilizing said plasma or the afterglow therefrom to remove material from the substrate.

7) The device of claim 6 wherein the electric field in the cavity is in the rectangular TM_{110} or cylindrical TM_{010} mode.

8) The device of claim 7 wherein the plasma tube is made of a material which is inclined to crack when heated unequally.

9) The device of claim 8 wherein said material has a linear thermal expansion coefficient greater than $7 \times 10^{-7}/K^{\circ}$ at operating temperature.

10) The device of claim 9 wherein the plasma tube is made of sapphire.

11) The device of claim 9 wherein said gas comprises fluorine or a compound thereof.

12) The device of claim 6 wherein said microwave cavity has conducting partitions therein which divide the cavity into sections, each partition has an opening therein, and said plasma tube passes through the openings of all said partitions.

13) The device of claim 12 wherein said cavity is elongated, and wherein said tube passes through the entire length of the cavity.

14) The device of claim 13 further including coupling means for coupling microwave energy to each of said cavity sections.

15) The device of claim 13 wherein the openings in the partitions are made large enough so that the plasma tube is separated from the partition so as to provide microwave leakage.

16) The device of claim 14 wherein said coupling means is a plate with coupling irises therein.

17) The device of claim 12 wherein said tube is coaxial with an outer tube which surrounds said tube, and wherein pressurized cooling gas is fed through the space between said tube and said outer tube.

18) The device of claim 12 further including a separate microwave power generating source for each section and a respective coupling means for coupling microwave power from the source to the cavity section.

19) The device of claim 14 or 18, further including a microwave choke surrounding the plasma tube at each partition.

20) A plasma discharge device for removing material from a substrate comprising, a microwave cavity, a plasma tube made of

sapphire passing through said cavity, means for flowing gas containing fluorine or a compound thereof through said sapphire tube, means for providing microwave energy to said cavity having an electric field component which is substantially azimuthally and axially symmetrical in relation to said tube for exciting said gas to a plasma, and means for utilizing said plasma or the afterglow therefrom for removing said material from said substrate.

21) The device of claim 20 wherein said cavity is elongated and has two ends, further including a microwave trap at each end of said cavity for preventing microwave energy from escaping from said cavity.

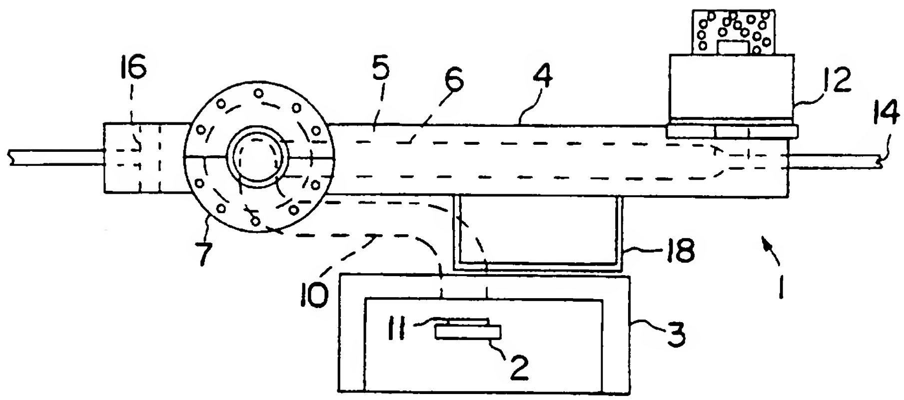

FIG. 1

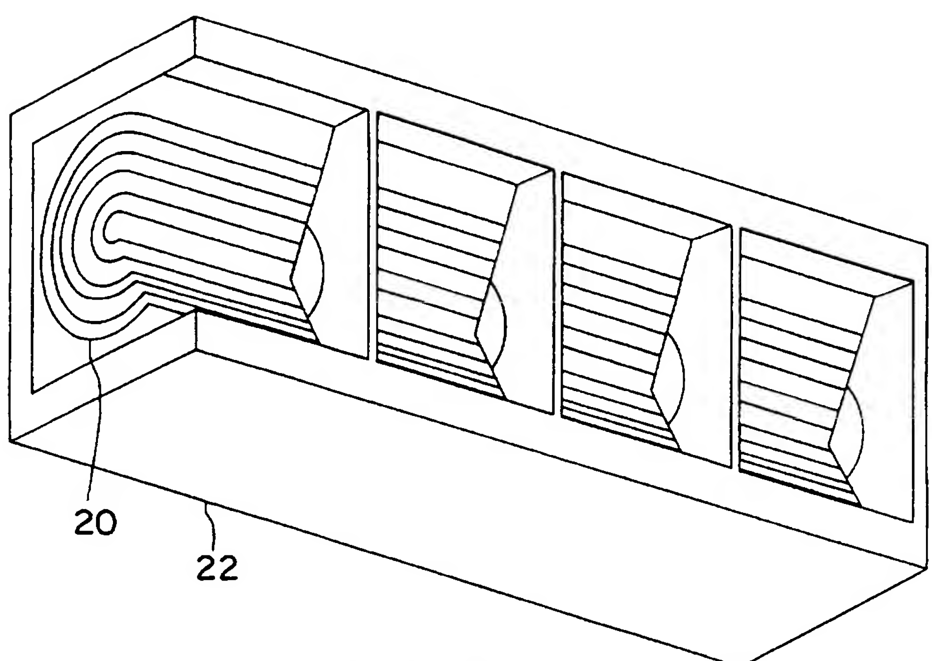

FIG. 2

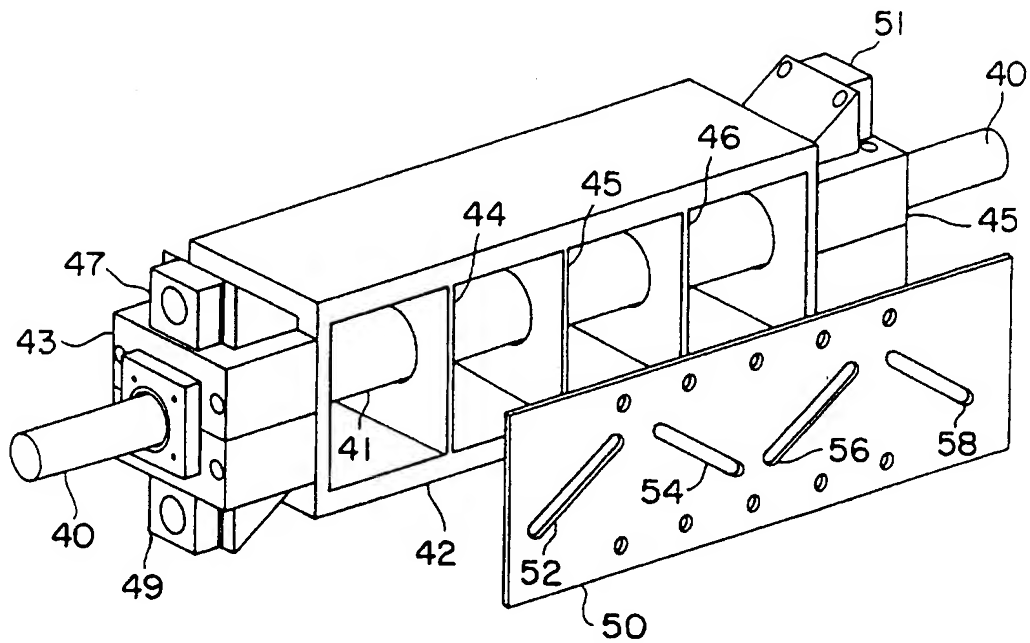
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FIG. 3

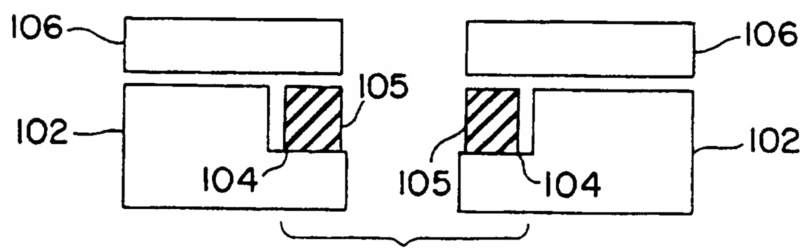
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FIG. 7

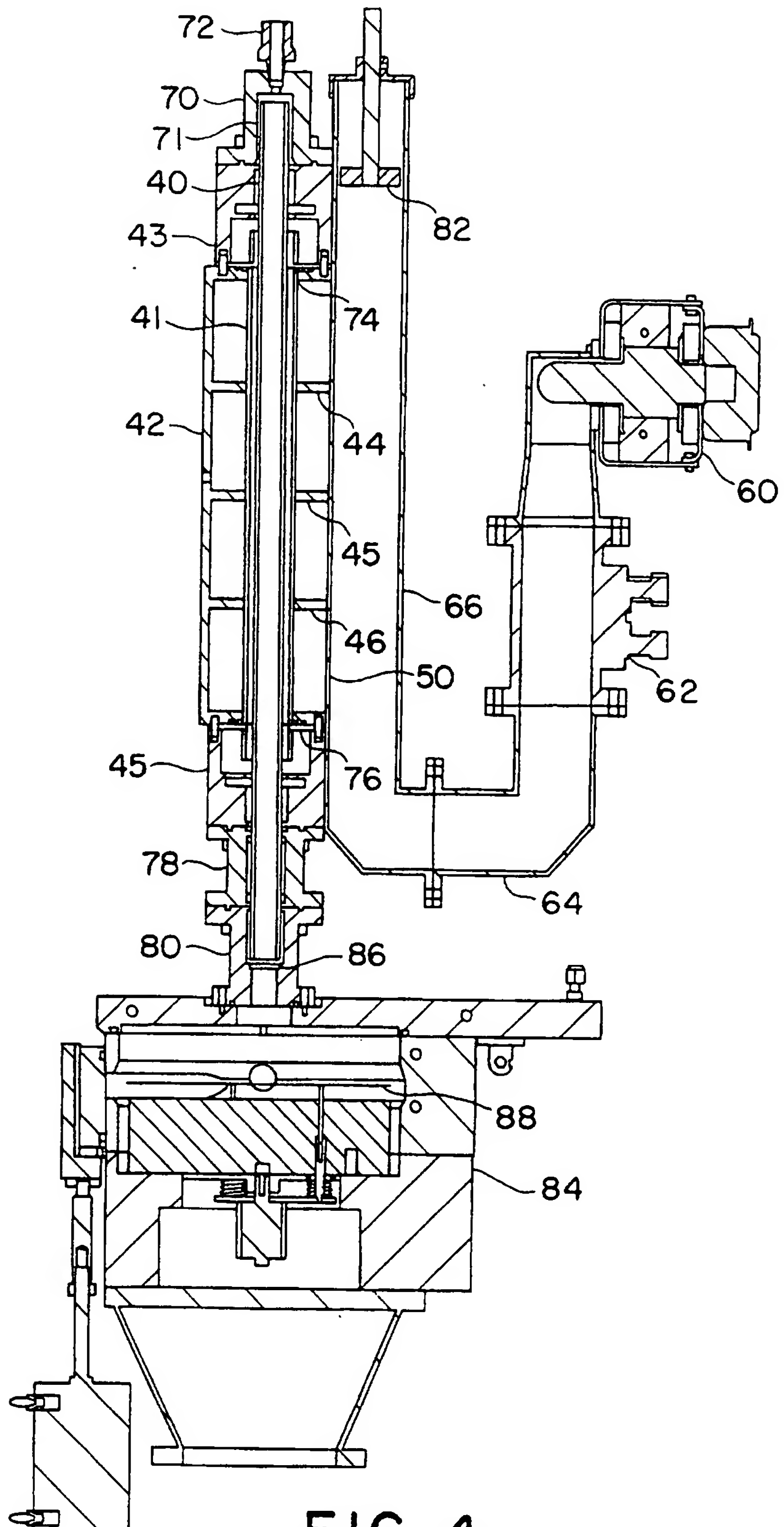

FIG. 4

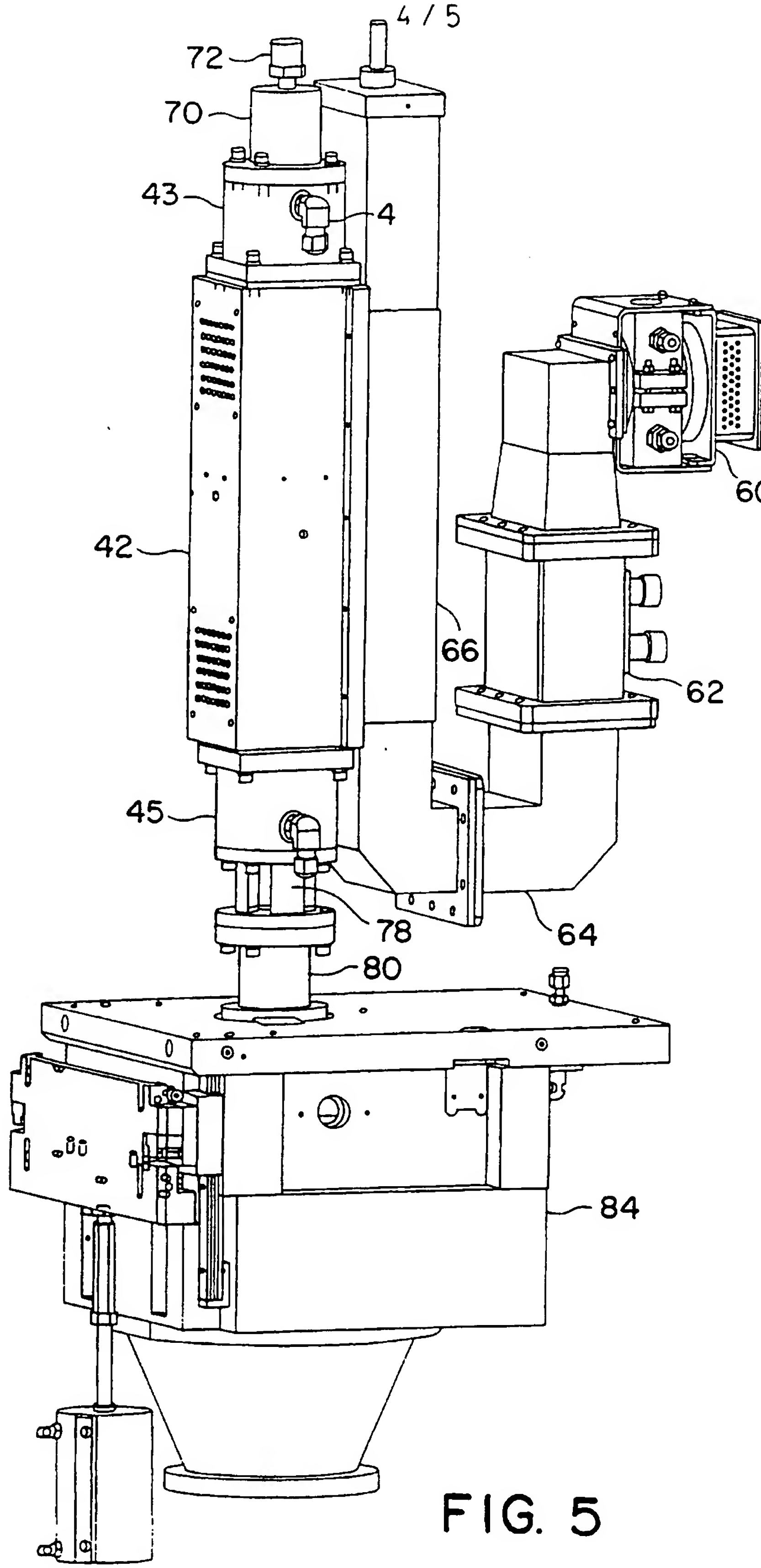

FIG. 5

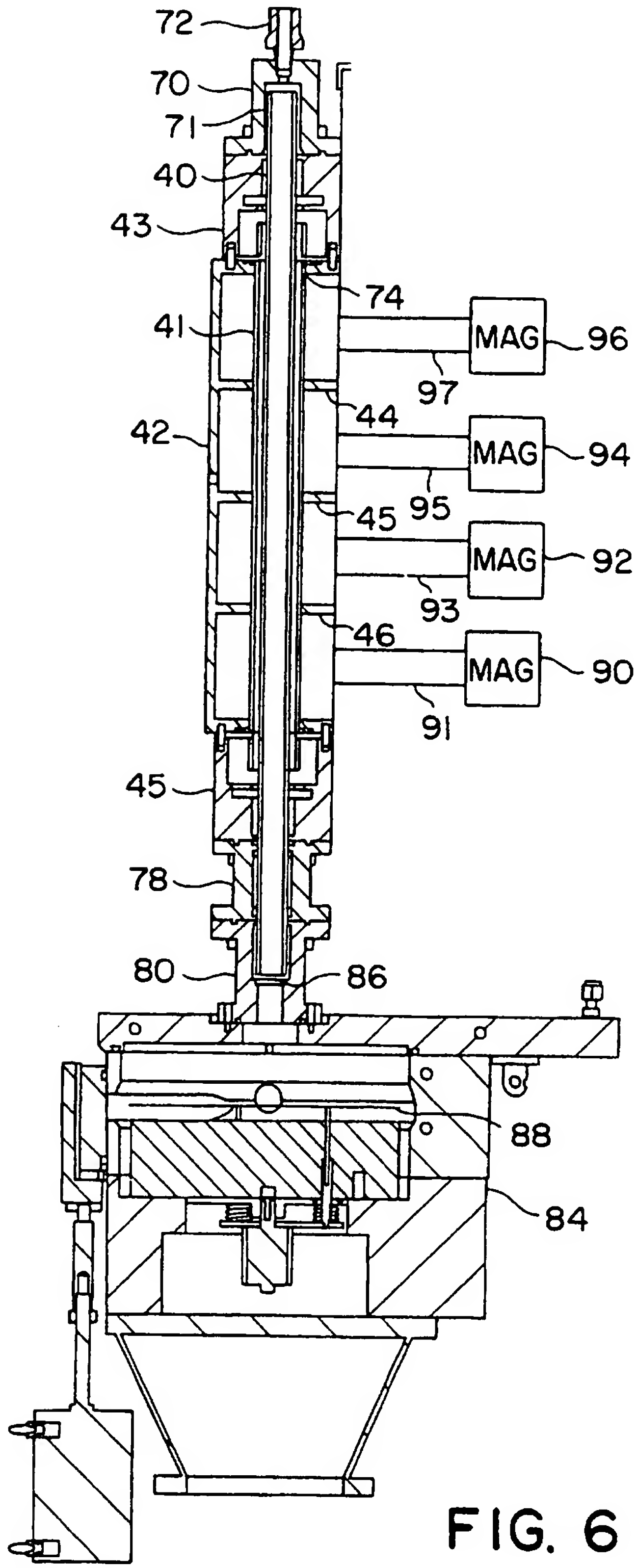
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FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/05517

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :C23C 16/00; C23F 1/02; H01L 21/00
US CL :156/345, 643.1, 646.1; 118/ 723R, 723 MW, 723ME; 204/298.38
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 156/345, 643.1, 646.1; 118/ 723R, 723 MW, 723ME; 204/298.38

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---- Y	US 5,498,308 A (KAMAREHI ET AL) 12 March 1996; column 2, lines 43-67; column 3, lines 1-3; column 4, lines 47-51;Figure 1.	1,2,6,7 ----------- 3-5
X ----- Y	US 5,017,404 A (PAQUET ET AL) 21 May 1991; column 6, lines 50-68; column 7, lines 1-20, 62-66; figures 1 and 7.	6,12-15,18, 19 ----------- 4,7-11,17
Y	US 4,985,109 A (OTSUBO ET AL) 15 January 1991; column 4, lines 37-64; figure 2	16
Y	US 5,134,965 A (TOKUDA ET AL) 04 August 1992; column 14, lines 6-13; column 15, lines 35-45; column 17, lines 49-63; column 19, line 45-63; figures 14-16 and 18-22	16

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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